



The Phase Diagram of High Temperature QCD with Three Flavors of Improved Staggered Quarks *

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We report on progress in our study of high temperature QCD with three flavors of improved staggered quarks. Simulations are being carried out with three degenerate quarks with masses less than or equal to the strange quark mass, m_s , and with degenerate up and down quarks with masses in the range $0.1 m_s \leq m_{u,d} \leq 0.6 m_s$, and the strange quark mass fixed near its physical value. For the quark masses studied to date we find rapid crossovers, which sharpen as the quark mass is reduced, rather than bona fide phase transitions.

The MILC Collaboration is studying high temperature QCD with three flavors of improved staggered quarks [1] using a one-loop Symanzik improved gauge action [2] and the Asqtad quark action [3]. This action is particularly well suited for the study of high temperature QCD because it has excellent scaling properties in the lattice spacing, significantly better dispersion relations for quarks and hadrons than standard actions, and substantially smaller taste symmetry violations than the Kogut-Susskind action.

We are considering two cases: 1) all three quarks have the same mass, m_q ; and 2) the two lightest quarks have equal mass, $m_{u,d}$, and the mass of the third quark is fixed at that of the strange quark, m_s . We refer to these cases as $N_f = 3$ and $N_f = 2 + 1$, respectively. This year

we have reduced the quark mass in the $N_f = 3$ study to $m_q = 0.2 m_s$, and that in the $N_f = 2 + 1$ study to $m_{u,d} = 0.1 m_s$. For the masses we have studied to date, we find rapid crossovers, which sharpen as the quark mass is reduced, rather than *bona fide* phase transitions.

We would like to keep the physical quark masses fixed as we vary the lattice spacing, and therefore the temperature. To this end, for the $N_f = 3$ case we work along curves of constant pseudoscalar to vector mass ratio, $m_{\eta_{ss}}/m_\phi$. These curves are determined from interpolations between the results of spectrum calculations at lattices spacings 0.12 and 0.20 fm. For $N_f = 2 + 1$ we make use of spectrum calculations at lattice spacings 0.09, 0.12 and 0.20 fm to determine curves of fixed m_π/m_ρ and $m_{\eta_{ss}}/m_\phi$. Here η_{ss} and ϕ are the pseudoscalar and vector mesons made up solely of strange quarks. The lattice

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spacing, and hence the temperature, are determined from the heavy quark potential for values of the gauge coupling and quark masses for which we have performed spectrum calculations, and by interpolation of the lattice spacing for other values of the gauge coupling and quark mass.

For three equal mass quarks, $N_f = 3$, we have carried out thermodynamics studies on lattices with four, six and eight times slices, and aspect ratio $N_s/N_t = 2$. Here N_s and N_t are the spatial and temporal dimensions of the lattice in units of the lattice spacing. To date we have studied quark masses in the range $0.2m_s \leq m_q \leq m_s$. In Fig. 1 we plot the chiral order parameter, $\langle\bar{\psi}\psi\rangle$ as a function of temperature on $16^3 \times 8$ lattices. The bursts are linear extrapolations of $\langle\bar{\psi}\psi\rangle$ from the runs with the two lightest quark masses to $m_q = 0$ for fixed temperature. This figure suggests that for $m_q = 0$ there is unlikely to be a phase transition for temperatures above 175 MeV, but one could occur at or below that value. For the quark masses we have studied, the data indicate a crossover, which sharpens as the quark mass decreases. The absence of a phase transition at these quark masses is consistent with the findings of the Bielefeld group [4]. The sharpening of the crossover with decreasing quark mass is seen more clearly in Fig. 2, where we plot the total $\bar{\psi}\psi$ susceptibility as a function of temperature on $12^3 \times 6$ lattices.

The $N_f = 2 + 1$ thermodynamics studies were carried out primarily on $12^3 \times 6$ and $16^3 \times 8$ lattices. In addition, a number of runs were made on $18^3 \times 6$ lattices to check for finite size effects, which turned out to be negligible. In this phase of the work we performed simulations with two degenerate light quarks in the range $0.1m_s \leq m_{u,d} \leq 0.6m_s$. In Fig. 3 we show the chiral order parameter as a function of temperature on $16^3 \times 8$ lattices. Here the bursts are a linear extrapolation from the runs with the two smallest light quark masses to $m_{u,d} = 0$ for fixed temperature and heavy quark mass. This figure indicates that there is unlikely to be a phase transition for $m_{u,d} = 0$ and the heavy quark mass equal to that of the strange quark for $T > 175$ MeV. The sharpening of the crossover as $m_{u,d}$ decreases is clear.

Quark number susceptibilities [5,6] are of par-

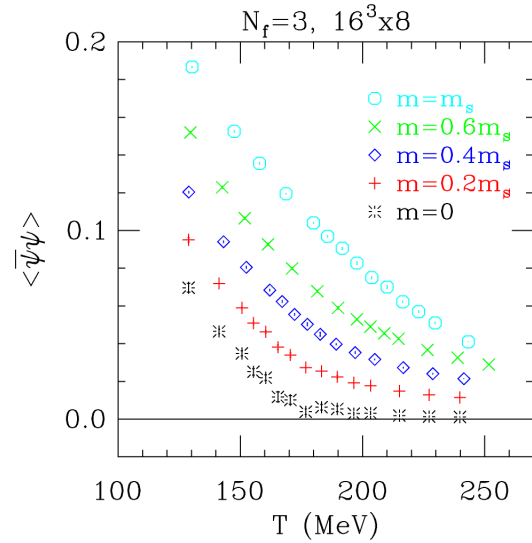


Figure 1. The chiral order parameter, $\langle\bar{\psi}\psi\rangle$, on $16^3 \times 8$ lattices for $N_f = 3$. The bursts are linear extrapolations of $\langle\bar{\psi}\psi\rangle$ to $m_q = 0$ at fixed temperature.

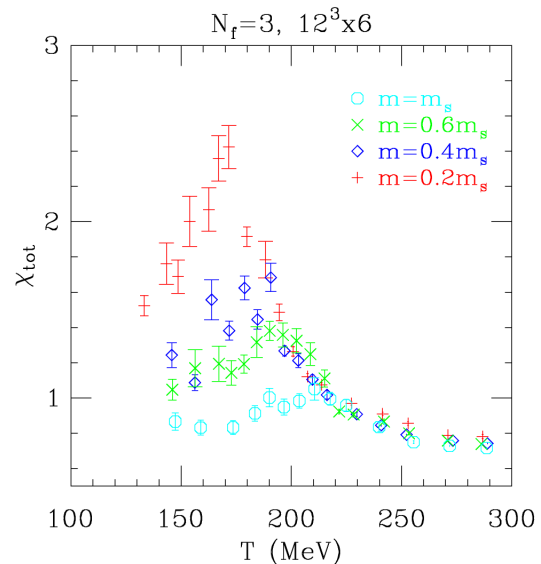


Figure 2. The $\bar{\psi}\psi$ susceptibility as a function of temperature on $12^3 \times 6$ lattices for $N_f = 3$.

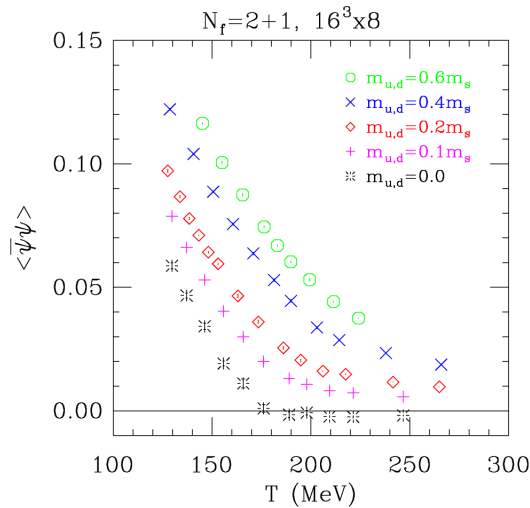


Figure 3. The chiral order parameter, $\langle \bar{\psi}\psi \rangle$, on $16^3 \times 8$ lattices for $N_f = 2 + 1$. The bursts are linear extrapolations of $\langle \bar{\psi}\psi \rangle$ to $m_q = 0$ at fixed temperature.

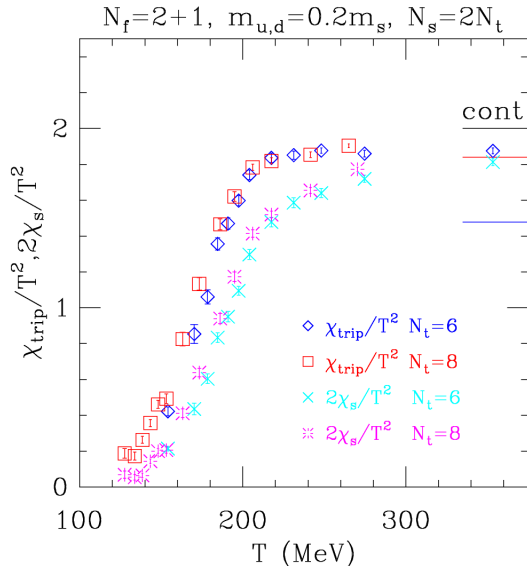


Figure 4. The triplet and strange quark number susceptibilities as a function of temperature for two light quarks with mass $0.2m_s$ and one heavy quark with mass m_s . Results are shown for $12^3 \times 6$ and $16^3 \times 8$ lattices. The lines on the right of the figure indicate the values for free quarks in the continuum, and on the finite lattices on which the simulations were carried out.

ticular interest because they are related to event by event fluctuations in heavy ion collisions, and can therefore be directly measured [7]. They also provide excellent signals for the crossover. In Figure 4 we show results for the triplet and strange quark number susceptibilities on both $12^3 \times 6$ and $16^3 \times 8$ lattices. The close agreement between the $N_t = 6$ and 8 results illustrates the excellent scaling properties of the action in the lattice spacing.

Of particular importance for the coming year will be the determination of the end point of the line of first order phase transitions expected for the $N_f = 3$ case, and the completion of the $N_f = 2 + 1$ study at $m_{u,d}/m_s = 0.1$.

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